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Economic Feasibility of a Siderostat-fed Liquid Mirror Telescope for Surveillance of Space

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Abstract

A concept for a Siderostat-Fed Liquid Mirror Telescope (SF-LMT), intended for surveillance of space, is described and a rough order of magnitude cost estimate is calculated; the technical aspects of the system are not discussed as the purpose of the investigation is to determine whether such a system has compelling cost savings over conventional 4-10 meter-class astronomical telescopes. The SF-LMT concept is driven by the extremely low cost associated with LMTs, the cost savings associated with creating a large flat mirror out of a number of smaller segments, and the cost savings associated with polishing a flat mirror over a parabolic mirror. The siderostat system, consisting of two flat mirrors that make up the steerable fore-optics of the system, feeds light to the LMT for image formation. The cost estimate methodology is taken from the astronomical literature and is modified to account for the technologies described above. It is shown that the cost savings that arise from the use of the LMT for image formation are offset by the costs of the large siderostat mirrors. It is concluded that the technical risk coupled with the lack of a compelling financial advantage over conventional telescope designs argue against developing the SF-LMT concept further.

Significance for defence and security

The Canadian Armed Forces (CAF) conducts Surveillance of Space (SofS) in conjunction with international partners, primarily the United States. The constantly increasing population of Resident Space Objects - both operational objects and debris - requires that ever more capable sensors and systems be deployed to ensure the safety of spacecraft of interest to Canada and its allies. The current study investigated the financial viability of a novel optical sensor design to determine whether the design would provide an attractive combination of capability and cost. This top level analysis determined that there would be no cost advantage of this novel design as compared to conventional optical sensor designs of similar capability. As such this design can be eliminated from any consideration for a future Canadian SofS sensor.

Résumé

Le présent rapport traite d'un concept de télescope à miroir liquide alimenté par cœlostat (TML AC) destiné à la surveillance de l'espace. Il comporte une estimation approximative de l'ordre de grandeur des coûts associés à ce concept. Il n'aborde cependant pas les aspects techniques du TML AC, puisque l'étude a pour objet de déterminer si ce télescope offre de réels avantages financiers par rapport à ceux des télescopes traditionnels dans les quatre à dix mètres. Le concept de TML AC est tributaire du coût extrêmement faible des TML, de même que des économies de coûts associées à la fabrication d'un grand miroir plat à partir de plus petits segments et au polissage d'un miroir plat (par rapport à un miroir parabolique). La lumière nécessaire au TML pour former des images est fournie par un cœlostat, un système composé de deux miroirs plats qui forment les éléments optiques d'entrée orientables. La méthode d'estimation des coûts provient de documents d'astronomie et a été adaptée aux technologies susmentionnées. Le rapport montre que les économies réalisées grâce à l'utilisation d'un TML pour former des images sont annulées par les coûts associés aux grands cœlostats. On en arrive à la conclusion que les risques techniques et l'absence de véritables avantages financiers par rapport à ce qu'offrent les modèles classiques de télescopes ne favorisent pas le développement approfondi du concept de TML AC.

Importance pour la défense et la sécurité

Les Forces armées canadiennes (FAC) effectuent la surveillance de l'espace (SdeE) de concert avec des partenaires internationaux, principalement les États-Unis. En raison de la présence sans cesse grandissante d'objets spatiaux en orbite (objets opérationnels et débris), il faut déployer des capteurs et des systèmes de plus en plus efficaces en vue d'assurer la sécurité des astronefs d'intérêt pour le Canada et ses alliés. La présente étude a porté sur la viabilité financière d'un nouveau concept de capteur optique afin de déterminer si celui-ci offrirait une combinaison intéressante de capacités et de coûts. Cette analyse au plus haut niveau a permis de déterminer que ce nouveau concept ne présenterait aucun avantage financier par rapport à ce qu'offrent les modèles traditionnels de capteurs optiques de capacité similaire. Nous pouvons donc retirer ce modèle de la liste des capteurs potentiels de SdeE canadiens.

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1 Introduction

The most basic function of Surveillance of Space (SofS) is to monitor the positions and orbits of man-made, Earth-orbiting objects (referred to as "Resident Space Objects", RSOs). Currently, the US Space Surveillance Network (SSN) maintains a public catalog of almost 9000[1] RSOs [1], ranging in size down to about 10 cm in Low Earth Orbit (LEO) [2]. The Canadian Forces (CAF) supports the SSN by providing personnel via the North American Aerospace Defense Command (NORAD) and will, in the near future, provide data using both ground- and space-based optical sensors.

The CAF has chosen to help maintain the "deep-space" portion of the RSO catalog, deep-space being defined as orbital altitudes greater than 5000 km. The deep-space realm includes the Global Positioning System (GPS) satellites, Russian Molniya satellites, and all satellites in Geosynchronous Orbit (GEO). The orbits of deep-space objects are best maintained using data from optical sensors, as the signal-to-noise ratio (SNR) of radar sensors suffers from an r^{-4} (r = range or distance) dependence on distance while optical sensors suffer only an r^{-2} dependence.

The distance dependence on SNR has the practical effect of limiting the size of RSOs that can be detected at different altitudes by a given sensor; as a result, the deep-space portion of the RSO catalog is complete to a much poorer level than the LEO portion – roughly a few meters in GEO [3]. Given that significant damage can be caused by collisions with objects down to 1 cm in size, there is interest in bringing the completion level of the deep-space catalog down to a level at least comparable with that of the LEO portion.

One way to accomplish this goal is to increase the sensitivity of the ground-based optical sensors that are used to maintain the catalog. The main optical sensors used in the SSN are the Ground Based Electro-Optical Deep Space Surveillance (GEODSS) sensors [4], which have two 1 m diameter reflecting telescopes at each site. The desire is thus to find cost-effective ways to create and operate optical telescopes having significantly larger diameters.

Building large optical telescopes is generally an expensive undertaking, with cost increasing as diameter to the 2.7th power (e.g. [5]). The world astronomical community has built a number of large (4-10 m diameter) optical telescopes, but the costs have typically been on the order of $30-100 M (all dollar figures are in year 2000 United

[1] This number was current as of the initial writing of this note in 2006. A number of catastrophic fragmentation events took place after this (including the Chinese anti-satellite test in 2007, and the Iridium-Cosmos collision in 2009) and the current count stands at over 16,000. The large increase innumber of debris objects over this period serves to highlight the importance of keeping better track of the orbits of these objects.

States Dollars - USD); such a pricetag may not be feasible for the CAF, and a lower cost would certainly be preferred. However, in a desire to create telescopes having ever larger apertures, astronomers have developed a number of technologies that could be used to reduce the cost of a large telescope dedicated to space surveillance.

The costs of optical telescopes (not including the cost of instrumentation, which can itself be significant) have historically been dominated by the costs associated with the large primary mirror. Specifically, large monolithic mirror blanks are expensive to develop, and polishing them to the required parabolic shape is a long, delicate, painstaking and costly procedure. As a result, monolithic mirrors have been largely (although not completely) supplanted by segmented mirrors (e.g. KECK [6], The Hobby-Eberly Telescope (HET [7], and the next generation of extremely large telescopes), and parabolic mirrors have been, in some cases, replaced with spherical mirrors that can be polished in an easier, and less expensive, manner (e.g. the HET and the South African Large Telescope (SALT) [8]).

One of the more interesting, although seemingly limited, technologies that has been developed to obtain large aperture at low cost is the liquid mirror telescope (LMT). This technology, championed by Dr. Ermanno Borra of the University of Montreal, uses a curved spinning dish filled with a reflective substance (such as liquid mercury) to form a parabolic surface suitable for astronomy [9]. An example of such a telescope is the 6 m diameter LMT being developed at the University of British Columbia [10] which cost a total of $500K USD (for comparison, the 3.7 m diameter Canada-France-Hawaii Telescope, CFHT, cost approximately $25M USD to build in 1979 [11], and the 4.1 m Southern Observatory for Astrophysical Research, SOAR, telescope cost $28M USD to construct [12]).

The issue with LMTs is, of course, that the telescope is limited to viewing the zenith since any tilt would result in gravitational deformation and, in the worst case, the liquid spilling out of the dish. LMTs do not currently have any practical way to overcome these limitations. Fields of view of 10-30 arcminutes, centered at the zenith, are currently achieved, and field correcting optics have the potential to allow small field of view (arcminutes or less) to be observed at fixed zenith angles up to 45 degrees [13], but this solution is cumbersome and - since it is limited to a single angle - seemingly not practical. A design that allows pointing within a limited field of regard (˜ 6 degrees diameter) centered on the zenith has also been proposed [14], but with a very small field of view (˜ 1 arcminute). Nonetheless, the cost savings inherent in LMTs drives consideration of ways in which LMTs, or indeed any zenith limited telescope, can be made useful for more general observing.

This document examines the possibility of using a siderostat to “feed” a LMT a sky image from non-zenith angles. A siderostat is a flat mirror that reflects a sky image to a set of optics that focuses and feeds the light to a suitable detector (such as

a CCD imager or spectrograph). The potentially more familiar heliostat, used by both solar observatories and solar power plants, is a specialized type of siderostat that is constrained through its mount to track the sun. Siderostats are currently used in astronomy to track the sky for the Naval Prototype Optical Interferometer (NPOI, [15]) and the Wisconsin H-alpha Mapper (WHAM, [16]) instruments; as such, siderostats are well-developed technology. This concept for a Siderostat-Fed LMT (SF-LMT) is examined in enough detail below to develop a rough order of magnitude (ROM) cost estimate to determine whether this concept might usefully be pursued further; further development of the technical issues awaits a judgment of the cost advantages, if any, of the SF-LMT concept.

2 The Concept

The basic concept of the Siderostat-Fed LMT (SF-LMT) is illustrated in Figure 1. The steering of the telescope field of view is conducted entirely by the moveable siderostat, while the stationary LMT performs the focusing and image formation. A second version of this concept is shown in Figure 2 ("the dual mirror concept"), where the moveable siderostat mirror feeds a stationary mirror that in turn feeds the LMT. As will be shown later, this concept results in a smaller siderostat mirror and increased elevation access, but at the cost of a second mirror and decreased azimuthal access. Other arrangements can be considered to increase the sky coverage, but these designs will serve as the baselines for the purposes of this paper.

The assumption being tested is that the costs associated with adding an appropriately sized steerable siderostat to a LMT is significantly less than the costs associated with simply creating a similarly sized steerable conventional telescope.

3 Some Technical Aspects

Before tackling the question of costs, a few technical aspects need to be considered. For the purposes of this discussion, however, the technical aspects of the LMT itself shall not be considered here as the bulk of costs (as shown below) are associated with the steerable aspect of the telescope; the flat mirror system (siderostat) will thus take up the bulk of the analysis. Note that these discussions are not meant to be exhaustive, but rather indicative of the types of issues that a SF-LMT will have to overcome.

3.1 Pointing

Pointing a telescope usually requires a physical movement of the whole optical assembly so that the boresight (the axis of cylindrical symmetry) is directed toward the

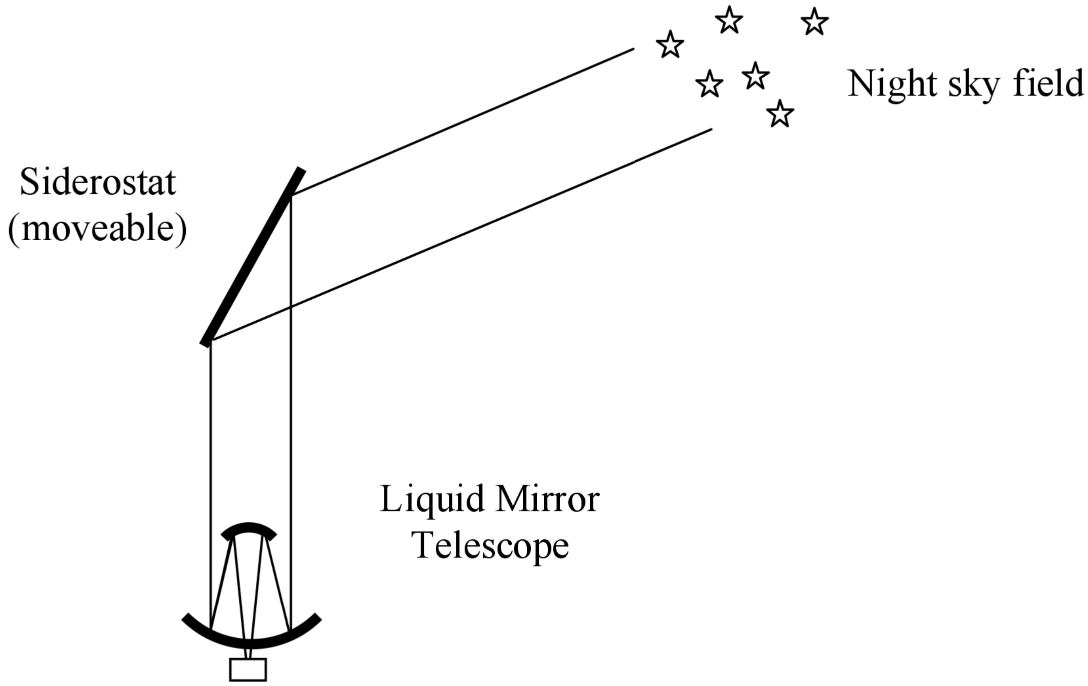

Figure 1: *A single mirror SF-LMT design.*

region of interest. A siderostat system is different in that the pointing is conducted by a flat mirror that reflects the light from the region of interest towards the focusing assembly (in this case the LMT). This is shown in Figures 1 and 2, and is detailed more in Figure 3.

From Figure 3 we can see that the mirror zenith angle (θ_z) is equal to $\frac{1}{2}$ the elevation angle of the region of interest:

$$\theta_Z = \frac{1}{2}\theta_E = \frac{1}{2}(\theta_i + \theta_r) \tag{1}$$

where $\theta_E = \theta_i + \theta_r$. The implication is that, for the single-mirror concept shown in Figure 1, the mirror needs to be inclined at an angle of 45 degrees simply to view the horizon, and at larger angles in order to image any other part of the sky; this has implications for mirror sizing due to projection effects (discussed below). Note also that such a system is unable to view the zenith (as a result of the projection effects discussed in the next section). For the dual-mirror concept, in contrast, at a mirror inclination of 45 degrees the siderostat would view the zenith, while at an inclination of 0 degrees it would view the horizon; the dual-mirror SF-LMT is thus the only configuration presented here that is able to view the entire sky.

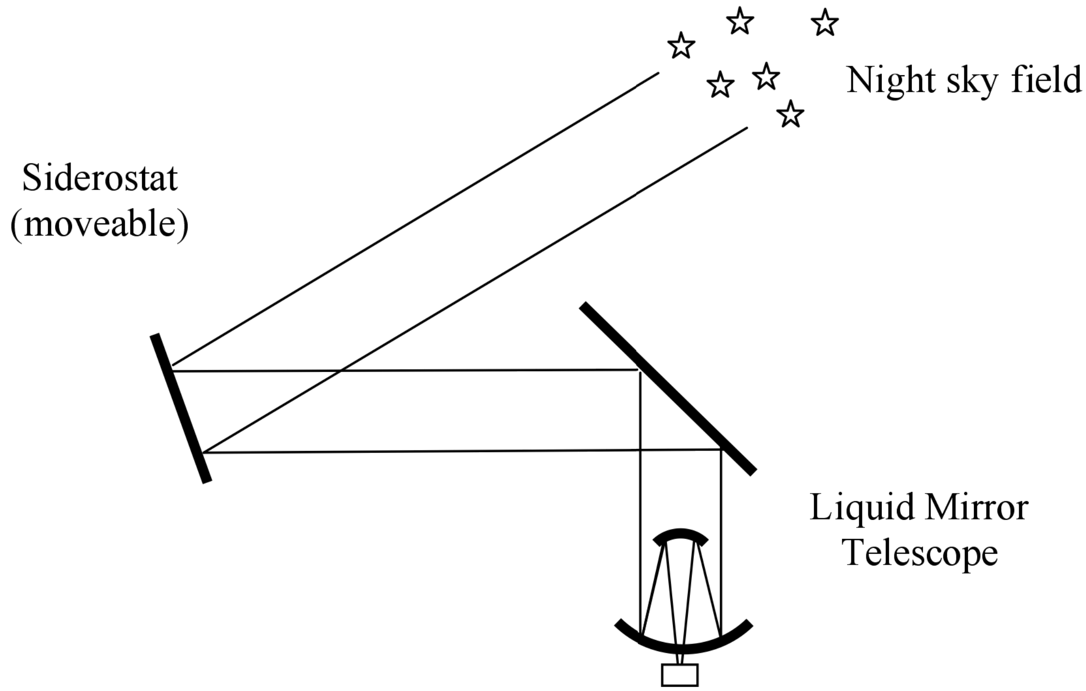

Figure 2: *A dual mirror SF-LMT design.*

3.2 Projection Effects

The purpose of the siderostat is simply to illuminate the LMT, allowing the system as a whole access to any region of the sky. At different angles, however, a single mirror siderostat of a given size L will have a projected size

$$P = L\cos\theta_E \tag{2}$$

as seen from the LMT (Figure 4). As a result, the siderostat mirror illuminating a LMT of diameter d must be sized

$$L = \frac{d}{\cos\theta_{Emax}} \tag{3}$$

so that it is capable of fully illuminating the LMT in all expected orientations.

Due to the distorting effects of the atmosphere the minimum useable elevation angle for an optical telescope is around 20 degrees. For the single mirror concept shown in Figure 1, illuminating an entire 4 m aperture would thus require a minimum siderostat size of approximately 7 m. Further, the projection effect demands that, as θ_E increases, the size (L) of the siderostat increases dramatically, and as a result it is impossible for the instrument to image the zenith. If a maximum elevation of 60

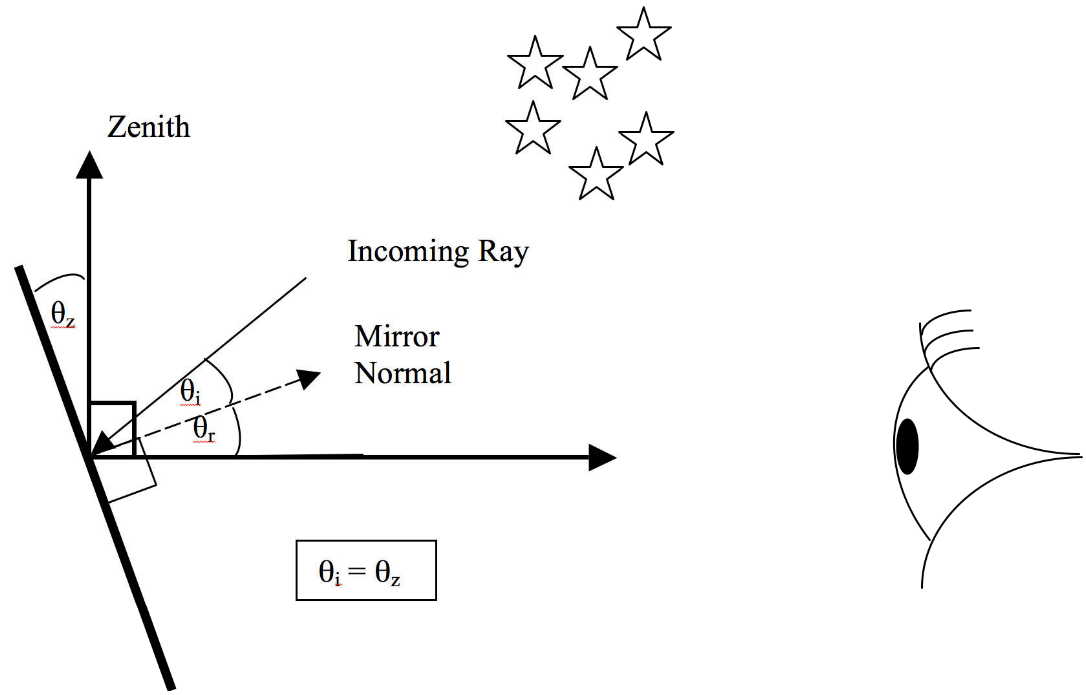

Figure 3: *Geometry of sky observing.*

degrees is assumed, the siderostat mirror in the single mirror concept would need to be approximately 15 m in size. This range of sizes (7 - 15 m) is worryingly large and will be shown to be cost prohibitive.

For the dual mirror concept things are slightly different. If the fixed mirror is oriented at 45 degrees (although other angles are certainly possible), it will need to be 5.6 m in size. The moveable siderostat mirror, on the other hand, need not be so large since it will simply need to illuminate the fixed mirror, which will have a projected size of 4 m. To view an elevation of 20 degrees the siderostat need only have an elevation of 10 degrees, and thus a diameter of 4.1 m; for 60 degrees the elevation would only need to be 30 degrees, and the size only 4.6 m. As such, for a given sky coverage it may be possible that the dual mirror concept would be much less expensive (compared to the single mirror concept), despite the requirement for a second (fixed) mirror.

It should be noted also that this projection effect would result in a related effect in the image plane (i.e. the plate scale will be compressed by the same projection effects). While this aspect does not have a direct impact for this discussion, it would need to be taken into account when considering instrumentation and data reduction requirements.

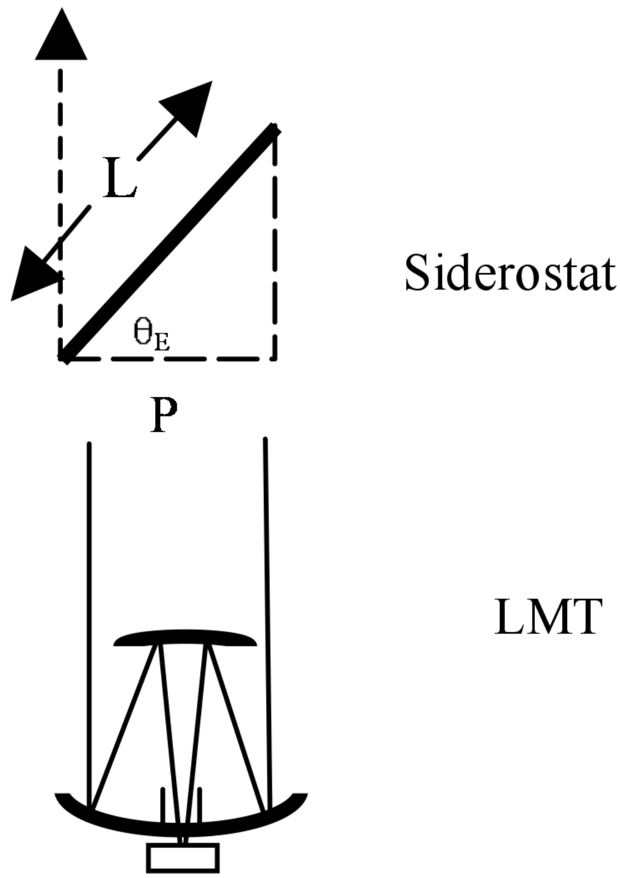

Figure 4: *Siderostat projection effects.*

3.3 Mount

Any elevation-steerable mirror assembly will result in the angle between the normal to the mirror surface and the Earth's gravity vector changing with observing angle resulting in some gravitational deformation of the mirror. For smaller mirrors simply increasing the thickness and thus rigidity of the mirror compensates for this effect. For larger mirrors, deformable mirrors are used, and actuators placed between the mount and the mirror apply pressure to maintain the shape of the mirror. As tracking agility decreases with increased mirror mass it is likely that actuators of some sort will have to be used in the SF-LMT, and along with this a mirror metrology system to track the deformations. Both actuators and metrology systems are routinely used in larger telescopes and thus the technology is mature.

3.4 Segmented mirrors

Some of the cost savings envisioned by the SF-LMT concept is achieved by moving the image formation task from the traditional, moveable, parabolic mirror to a stationary LMT – in this way there is no need to polish the primary mirror to a parabolic shape. However, the trade-off is that large siderostat mirror(s) are required to image non-zenith regions. The siderostat mirrors will thus share the same disadvantages inherent in traditional large parabolic mirrors – the difficulty in creating a large mirror blank, the specialized equipment needed to polish these large blanks, and the need to minimize mass while maintaining rigidity (among others). For this reason the SF-LMT concept takes advantage of what is probably the major enabling technology for large telescopes - the use of segmented mirrors in place of monolithic mirrors.

A conventional large optical telescope makes use of a single, large, piece of optical material that is then polished to the required shape and coated with a highly reflective film to form the primary mirror; this large single piece mirror is referred to as a "monolithic" mirror. Making large monolithic mirrors is a very challenging process as the optical material must be very pure, must be free of bubbles or other imperfections, and must be ground to a parabolic shape down to 1/10th of a wavelength quality (i.e < 50 nm rms). As might be expected, this is a very challenging procedure, usually requiring (expensive) custom equipment for the large mirrors ($>$ few meters) required for cutting edge astronomy, and fabrication and polishing of this large mirror largely drives the cost of the telescope.

Recognizing this, the W.M. Keck observatory pioneered the use of segmented mirrors in place of monolithic mirrors for its twin 10m diameter telescopes in Hawaii. In a segmented mirror the primary light collecting area is made of many small (usually hexagonal) mirror segments as shown in Figure 5. The collecting area is roughly the same, and the individual segments must be ground to the same tolerance as the corresponding monolithic mirror. The cost savings arise from the fact that smaller mirrors are easier to fabricate and polish, and since a large number of segments are required some economies of scale are realized. These savings are somewhat countered by the added complexity in the active support structure required to maintain the relative alignments of the individual segments under varying gravitational and thermal loads, but a net gain exists nonetheless.

The success of the Keck telescopes has resulted in segmented mirrors becoming a key enabling technology for the next generation of astronomical telescopes. These telescopes, referred to collectively as extremely large telescopes (ELTs), will have diameters from 20-100 m, and would not be possible without the use of segmented mirrors.

On a more modest scale, the SF-LMT concept makes use of segmented mirror technology for the flat siderostat mirrors. Since the polishing of a flat mirror is less onerous

than polishing a parabolic mirror, cost savings will be realized by the less demanding nature of making several small mirrors over a single large one, and by the decreased costs associated with polishing the smaller mirrors.

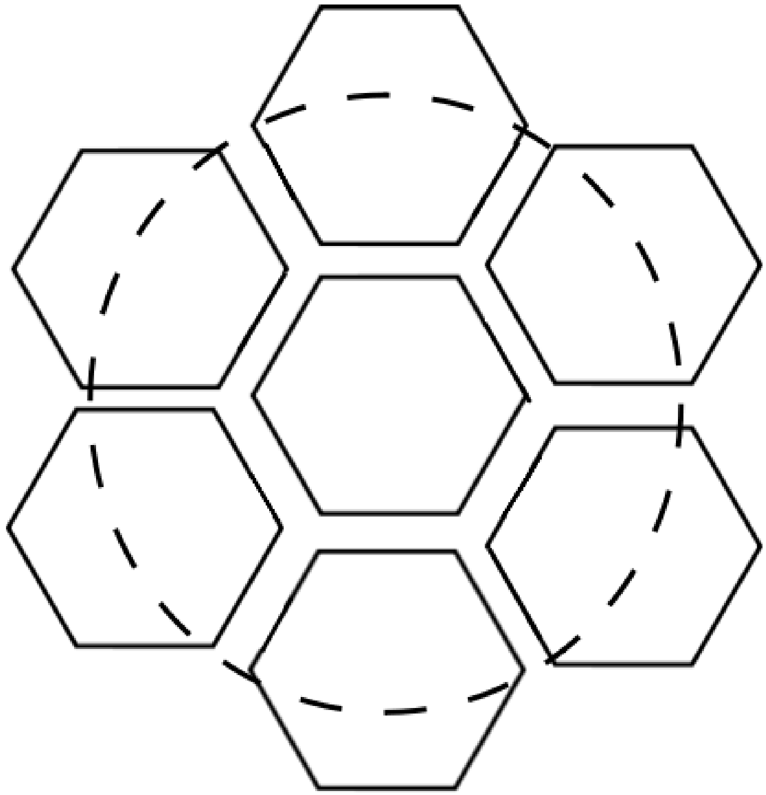

Figure 5: *In a segmented mirror a number of small hexagonal mirrors are used to collect and focus light. The individual segments are shown in solid lines, and approximate the collecting area of a single monolithic mirror shown in the dashed line.*

4 The Cost Model

The SF-LMT concept outlined in Section 2 is the result of a desire to create a low-cost, steerable, optical telescope for surveillance of space. The assumption made in this design is that the total cost of the telescope can be significantly reduced by separating and simplifying the portion of the telescope which is steerable (the siderostat) from the portion of the telescope which does the focusing and image formation (the LMT). This assumption is tested here.

Sebring et al. [17] provide an empirical formula to estimate the costs (C) of a large (8-10 m) optical telescope:

$$C = 0.015D^4 + 0.0074D^{2.5} + 0.25D^2 + 0.049D + 16 \quad (4)$$

where D represents the diameter of the primary mirror (in meters), C represents the cost of the telescope system in $\$10^6$ USD (normalized to year 2000 US dollars), and the individual terms represent the costs of the primary mirror, support structure, polishing, cabling, and engineering (respectively, from left to right). Comparing the predictions made by this formula to the actual costs and diameters of a number of 3-8 m telescopes made since 1975 (as listed in [18]) this equation tends to underestimate the costs by roughly 10 percent, with a standard deviation of roughly 20 percent, suggesting that Equation 4 provides useful ROM cost estimation for telescopes in this size range.

Other telescope cost models exist in the literature (e.g. [19], [20]). All the models fit the actual data more or less well, but none seem to be definitely better or worse. An in-depth comparative analysis of these cost models is beyond the scope of this report. As a result, given that [17] fits the data to within the accuracy needed for a ROM cost estimation we will use [17] for our investigation.

Telescopes made prior to 1975 were not included in this comparison as their costs do not reflect modern manufacturing methods, and telescopes larger than about 10m were not included as they are sufficiently cutting-edge that the costs are inflated by the R&D and associated specialized manufacturing costs of these cutting edge telescopes. As a result, the analysis below is confined to telescopes with primary mirror diameters between 4 and 8 m; the lower limit is set to surpass the AEOS 3.67 m telescope in Maui, currently the largest telescope in the world that is dedicated to SofS.

Using this relationship, a 4 m class telescope would cost roughly \$30M USD, in line with the costs of the CFHT and SOAR provided in Section 1. In Table 1 the component costs (in 10^6 USD) of a conventional 4, 6 and 8 m diameter telescope are provided, derived using Equation 4. Note that enclosure and instrumentation costs are not explicitly included here.

Table 1: *Cost estimates for major telescope components (10^6 Year 2000 USD).*

Component	4 m	6 m	8 m
Primary Mirror	3.84	19.44	61.44
Support Structure	0.27	0.65	1.34
Polishing	9.28	20.88	37.12
Cabling	0.20	0.29	0.392
Engineering	16	16	16
Total	29.59	57.26	116.29

As can be seen in Table 1, the majority of the costs (aside from engineering) are

associated with the mirror (primary mirror costs plus polishing costs). As a result, it is these costs that most require reduction. For the purposes of this discussion a conservative value for a 4-6 m diameter LMT on the order of $1M USD is assumed, and the focus is instead on the costs of the siderostat. The major cost for a SF-LMT will thus be for the siderostat mirror itself. As shown in Equation 4, the cost of the unpolished mirror is proportional to the mirror diameter to the fourth power.

Thus, just as the Keck telescopes realized significant cost saving through the use of segmented mirrors, a flat siderostat made up of a number of small segments will have a smaller cost than a single monolithic mirror. Studies done for the newest generation of large segmented telescopes (e.g. [21]) suggest segment sizes on the order of 1-2 m present an optimal compromise between mirror costs and increased system (i.e. mount, actuator, metrology system) complexity and engineering. Thus, the use of 2 m sized segments would reduce the cost of the 6m-sized siderostat mirror from $19M USD to approximately $2M, or an 8 m from $61M to $4M.

The second major cost term is the polishing of the mirror(s) to an accuracy required for astronomical uses - 50 nm rms. This cost scales as diameter squared, and thus the total polishing cost for a segmented mirror will be approximately the same as for a monolithic mirror.

However, polishing costs for a siderostat will be significantly reduced from that estimated by Equation 4 simply because the mirror is flat, not parabolic. Reference [21] highlights the fact that the process for polishing a parabolic curved mirror is considerably different than the process used for a flat mirror. This report was looking at spherically curved mirror designs which can be polished using essentially the same process as for flat mirrors (called "continuous polishing"). The authors of [21] contacted several optical finishers (i.e. polishers) who quoted costs a factor of 5 less than those for polishing traditional parabolic mirrors. As a result, the cost of polishing a 6 m siderostat will be approximately $4M, and an 8 m siderostat would cost $15M. Note that this estimate assumes a segmented mirror, as special equipment would probably be required for a large monolithic mirror.

The remaining significant cost is the engineering, $16M, which is provided by the constant term in Equation 4. No changes are made to this estimate.

We can provide a "sanity check" on the modifications made to the cost estimate methodology by calculating total cost estimates for two telescopes that use segmented spherical mirrors, the HET and the SALT. While both telescopes have total diameters of about 11 m, the optical quality of the HET is less than that of SOAR because HET is exclusively a spectroscopic instrument, while SALT is more general purpose and will be used for imaging. The SALT telescope is under construction with total cost estimates [22] on the order of $30M USD, and the total cost of the HET is $15M [18], but these numbers are likely underestimates due to the extended commissioning and

modifications that these telescopes have undergone during their initial operational phases.

Using Equation 4 and the modifications described above, the cost of a SALT-like 11 m telescope would be on the order of \$45M. Given that SALT itself cost \$30M, it can be concluded that the methodology provided here may overestimate the total cost by approximately 30%; this 30% overestimate is not compensated for in the tables below.

Table 2: *Comparison of costs for a 4 meter diameter conventional telescope versus SF-LMTs having maximum elevation angles of 48 degrees (10^6 Year 2000 USD).*

Component	Conventional	Single mirror SF-LMT	Dual Mirror SF-LMT
LMT	N/A	1	1
Primary Mirror / Siderostat	3.84 (1 if segmented)	7.47	1.15
45° Flat Mirror	N/A	N/A	6.02
Support Structure	0.27	3.08	0.3
Polishing	9.28	14.45	2.22
Cabling	0.20	0.55	0.21
Engineering	16	16	16
Total	29.59 (26.75 segmented)	42.55 (+44 percent) (+60 percent)	26.91 (-9 percent) (+1 percent)

Assuming that the non-mirror-related costs are fixed as in Equation 1, the costs of a conventional telescope can be compared with the two SF-LMT concepts, both having a maximum elevation of 48 degrees (which covers most of the GEO belt as seen from Southern Canada); these costs are estimated in Table 2 for a 4 m telescope.

It is clear from the table that the apparent cost advantage of a dual mirror 4 m diameter SF-LMT is minimal and that a single mirror SF-LMT has no cost advantage.

It is worthwhile to perform a cost comparison for larger SF-LMTs as well. Limiting the scope to SF-LMTs having a 48 degree elevation limitation, the costs of a conventional (monolithic primary mirror) telescopes can be compared to SF-LMTs having diameters of 4, 6 and 8 meters (note that the costs associated with the 45 degree flat mirror include the cost of the mirror, polishing, support structure and cabling, but not engineering as the engineering costs are assumed to be rolled up in the \$16M total costs of the telescope). As can be seen in Table 3, the apparent cost savings for a dual-mirror SF-LMT grows significant for the larger diameters, assuming monolithic primary mirrors for the conventional telescopes. It is worth noting that a requirement

to observe up to 60 degrees elevation (for example) will result in only a small cost increase (10% or so) but will greatly increase the utility of the instrument for SofS.

However, if we instead assume segmented primary mirrors for the conventional telescopes the costs savings of a SF-LMT disappear completely (Table 4). This result, along with the sky viewing limitations (elevation angles < 48 degrees) and the risk inherent in any new optical design, argues strongly against further development of the SF-LMT concept.

5 Conclusion

This note investigated the costs associated with an innovative design for a siderostat-fed liquid mirror telescope, and compared these costs with the costs associated with a conventional telescope. The cost estimation method is taken from the astronomical literature and modified so as to be applicable to flat, segmented, siderostat mirrors. The cost estimation method is estimated to be good to within 30 percent, sufficient for rough order of magnitude estimates.

The cost estimates suggest that a dual-mirror SF-LMT may have cost benefits over a traditional telescope having a large (> 6 m) diameter monolithic mirror, but that there are no benefits when compared to a similarly sized conventional telescope with a segmented primary mirror. Even if the 30 percent uncertainty in the method is taken to be real and of benefit to the SF-LMT concept, this benefit must be weighed against the unexpected costs that would undoubtedly be associated with a non-conventional design, the reduced sky coverage of a SF-LMT over a conventional telescope, and the uncertainty in operations of a LMT itself. These additional risks are likely to outweigh the (best-case) estimated cost savings, and significantly reduce the attractiveness of the SF-LMT concept.

Unless significantly larger cost savings than derived here can be demonstrated for the SF-LMT concept, and unless the risks associated with the concept can be alleviated, it is concluded that the siderostat-fed liquid mirror telescope design does not have sufficient cost savings over conventional (segmented mirror) optical telescopes, and that further development of this concept is not warranted at this time.

Table 3: *Telescope costs vs primary mirror diameter for conventional monolithic telescopes and a dual-mirror SF-LMT (percentage cost benefit of SF-LMT in parentheses) (10^6 Year 2000 USD).*

Telescope size/type	4 m		6 m		8 m	
Components	Conv	SF-LMT	Conv	SF-LMT	Conv	SF-LMT
LMT	N/A	1.0	N/A	1.0	N/A	2.0
Primary Mirror / Siderostat	3.84	1.15	19.44	2.59	61.44	4.6
45° Flat Mirror	N/A	6.02	N/A	13.95	N/A	25.34
Support Structure	0.24	0.3	0.65	0.82	1.34	1.68
Polishing	9.28	2.22	20.88	5.00	37.12	8.90
Cabling	0.20	0.21	0.29	0.32	0.39	0.43
Engineering	16	16	16	16	16	16
Total (percentage cost saving)	29.56	26.91 (-9)	57.26	39.68 (-40)	116.29	58.95 (-49)

Table 4: *Telescope costs vs primary mirror diameter for segmented conventional telescopes and a dual-mirror SF-LMT (percentage cost benefit of SF-LMT in parentheses) (10^6 Year 2000 USD).*

Telescope size/type	4 m		6 m		8 m	
Components	Conv	SF-LMT	Conv	SF-LMT	Conv	SF-LMT
LMT	N/A	1.0	N/A	1.0	N/A	2.0
Primary Mirror / /Siderostat	0.96	1.15	2.16	2.59	3.84	4.6
45° Flat Mirror	N/A	6.02	N/A	13.95	N/A	25.34
Support Structure	0.24	0.3	0.65	0.82	1.34	1.68
Polishing	9.28	2.22	20.88	5.00	37.12	8.90
Cabling	0.20	0.21	0.29	0.32	0.39	0.43
Engineering	16	16	16	16	16	16
Total (percentage cost saving)	26.68	26.91 (-0.1)	39.98	39.68 (-0.1)	58.69	58.95 (+0.1)

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List of symbols/abbreviations/acronyms/initialisms

AEOS	Advanced Electro-Optical System
CAF	Canadian Armed Forces
CCD	Charge Coupled Device
CDN	Canadian Dollar
CFHT	Canada-France-Hawaii Telescope
DND	Department of National Defence
ELT	Extremely Large Telescope
GEO	Geostationary Earth Orbit
GEODSS	Ground Based-Electro-Optical Deep Space Surveillance
GPS	Global Positioning System
HET	Hobby-Eberly Telescope
LEO	Low Earth Orbit
LMT	Liquid Mirror Telescope
NORAD	North American Aerospace Defence command
NPOI	Naval Prototype Optical Interferometer
ROM	Rough Order of Magnitude
RSO	Resident Space Object
SALT	South Africa Large Telescope
SF-LMT	Siderostat Fed Liquid Mirror Telescope
SNR	Signal to Noise Ratio
SOAR	Southern Observatory for Astrophysical Research
SofS	Surveillance of Space
SSN	Space Surveillance Network
UBC	University of British Columbia
USD	United States Dollar
WHAM	Wisconsin H-Alpha Mapper

Glossary

Azimuth	In astronomy, the angular distance, measured clockwise along the horizon, from a specified point on the horizon
Elevation	In astronomy, the angular distance, measured upwards, from the horizon. The zenith direction (straight up) will have an elevation of 90 degrees.
Heliostat	A device used to track the sun, usually to orient a mirror to reflect the suns light to a scientific device to power generating unit
Resident Space Object	A man-made Earth orbiting object such as satellites, rocket bodies and associated debris
Siderostat	A device similar to a heliostat, but used for tracking stars instead of the sun
Surveillance of Space	The detection, tracking, and identification of Earth-orbiting man-made objects

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A concept for a Siderostat-Fed Liquid Mirror Telescope (SF-LMT), intended for surveillance of space, is described and a rough order of magnitude cost estimate is calculated; the technical aspects of the system are not discussed as the purpose of the investigation is to determine whether such a system has compelling cost savings over conventional 4-10 meter-class astronomical telescopes. The SF-LMT concept is driven by the extremely low cost associated with LMTs, the cost savings associated with creating a large flat mirror out of a number of smaller segments, and the cost savings associated with polishing a flat mirror over a parabolic mirror. The siderostat system, consisting of two flat mirrors that make up the steerable fore-optics of the system, feeds light to the LMT for image formation. The cost estimate methodology is taken from the astronomical literature and is modified to account for the technologies described above. It is shown that the cost savings that arise from the use of the LMT for image formation are offset by the costs of the large siderostat mirrors. It is concluded that the technical risk coupled with the lack of a compelling financial advantage over conventional telescope designs argue against developing the SF-LMT concept further.

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